LASER PRINCIPLES

Chapter Four

Radiation Interaction With Matter

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CHAPTER FOUR: RADIATION INTERACTION WITH MATTER

4-1) Introduction

The theoretical idea of the laser was built on concepts related to the properties of electromagnetic radiation and its distinctive properties for laser output. On this basis, it is necessary to know the theoretical basis for understanding the laser through the interaction of electromagnetic radiation and how it deals with atoms and molecules such as absorption and emission. The scientist Planck formulated the theory of the spectral distribution of thermal radiation, and then Einstein combined Planck's theory with Boltzmann statistics to arrive at the theory of stimulated emission, which is the basic principle of the laser.

4-2) Blackbody Radiation

A blackbody is a hypothetical ideal object that satisfies three conditions: it absorbs all incident electromagnetic radiation, it emits thermal radiation proportional to its temperature across all wavelengths, and the emitted radiation is isotropic (equal in all directions).

If we assume a cavity filled with a homogeneous insulating medium, and that the walls of this cavity are maintained at a temperature T, then these walls continuously emit electromagnetic radiation and also absorb incident radiation. When the absorption and emission rates become equal, the equilibrium condition is said to be met at any point within the cavity, and the radiation emitted by this cavity is called blackbody radiation. The radiation at this equilibrium state can be described by its energy density ρ (the amount of energy per unit volume) of the cavity. Since this energy is a type of electromagnetic radiation, it can be expressed in terms of the electric field E(t) and the magnetic field H(t) according to the relationship:

$$\rho = \frac{1}{2}\varepsilon E^2(t) + \frac{1}{2}\mu H^2(t) \quad \text{...........} \ (4\text{-}1)$$

Where ε and μ are the electrical permittivity and magnetic permeability of the medium filling the cavity, respectively.

Classical physics failed to explain the experimental results of the blackbody emission theory at short wavelengths across different temperatures, where the radiation was considered as waves forming a standing wave pattern in the cavity with nodes at the walls. The classical formula for the radiation energy density is called the Rayleigh-Jeans law.

$\rho(\upsilon) = \frac{8\pi KT}{c^3}\upsilon^2$ ……….. (4-2)

The scientist Planck proposed that atoms oscillate at a certain frequency, and he also proved that each atom can absorb or emit energy as rays proportional to its frequency υ only by a constant of proportionality called (Planck's constant h) according to the following equation:

$E = nh\upsilon$ ……….. (4-3)

Thus, when an oscillator absorbs or emits electromagnetic energy, it increases or decreases by θ, 2θ, and 3θ in quanta. Planck's energy density (quantum formula) is given by the following equation:

$\rho(\upsilon) = \frac{8\pi KT}{c^3}\frac{1}{e^{\frac{h\upsilon}{KT}}-1}$ ……….. (4-4)

From Planck's law, we find that the radiation energy of a black body is a function of frequency, that is, the energy of electromagnetic radiation is distributed over different values of frequency. This is known as the spectral energy distribution. The spectral energy distribution function is a general function that does not depend on the shape of the cavity or the nature of its walls, but rather depends on the frequency and temperature of the cavity only. It has been found that the total energy emitted E per unit time from a unit area of the cavity surface is proportional to the fourth power of the absolute temperature.

$E = \varrho T^4$ ……….. (4-5)

The symbol ϱ represents the Stefan-Boltzmann constant and its value is (5.67×10^{-8} J K_4/m^2). The wavelength corresponding to the peak of the emitted radiation is denoted by the symbol λ_{max} and is given by Wien's law:

$\lambda_{max}T = 2.9 \times 10^3\ m\ K$ ……….. (4-6)

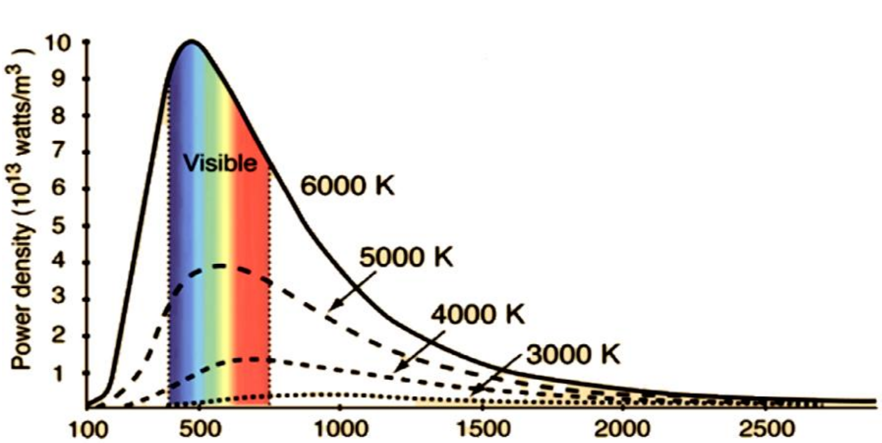

Figure (4-1): Blackbody emission spectrum.

4-3) Boltizman Statistics

The number of atoms per unit volume in the first energy level (E_1) of a two-level system is N_1, and the number of atoms per unit volume in the second energy level (E_2) is N_2. The energy difference between the two levels is ($E_2 - E_1 = h\upsilon$), and the overall energy density of the system is ($N = N_1 + N_2$). If the atoms are in thermal equilibrium with the surrounding temperature, the relative distribution in the two levels is called the Boltzmann distribution:

$$\frac{N_2}{N_1} = e^{-\frac{h\upsilon}{KT}} \quad \text{………... (4-7)}$$

This equation shows that increasing the temperature leads to an increased distribution in the excited (higher) energy levels. In thermal equilibrium, the distribution ratio in these levels is lower than in the lower energy levels. However, if the energy gap is large ($h\upsilon \le KT$), the above ratio approaches zero, so there are very few atoms in the higher energy levels. If two or more energy levels have the same energy, these levels are called degenerate levels. This means that multiple energy levels can exist within a single energy level, and all these levels have the same distribution. The equation above then becomes:

$$\frac{N_2}{N_1} = \frac{g_2}{g_1} e^{-\frac{h\upsilon}{KT}} \quad \text{………... (4-8)}$$

where g_1 and g_2 represent the plurality or statistical weight of levels E_1 and E_2, respectively. The statistical weight (g) represents the different ways in which atoms with the same energy can be distributed and depends on the quantum numbers.

4-4) Transition Cross Section

The transition cross-section σ of a uniform electromagnetic wave of intensity I is proportional to the photon flux density of the wave. The cross-sectional area depends on the type of material and the frequency of the incident wave. The cross-sectional area of stimulated emission is equal to the cross-sectional area of absorption. The interaction of electromagnetic radiation with the material can be described by the absorption coefficient α, which is related to the cross-sectional area by the equation:

$$\alpha = \sigma(N_1 - N_2) \quad \text{………... (4-9)}$$

That is, the absorption coefficient depends on the qualification of the system's energy levels and can be directly measured as a function of the wave intensity using Lambert's law:

$I_x = I_\circ e^{-\alpha x}$ ……….. (4-10)

If the medium is in thermal equilibrium, the qualification of the energy levels of the atom is described by Boltzmann statistics, which are:

$\frac{N_2}{N_1} = e^{-\frac{(E_2-E_1)}{KT}}$ ……….. (4-11)

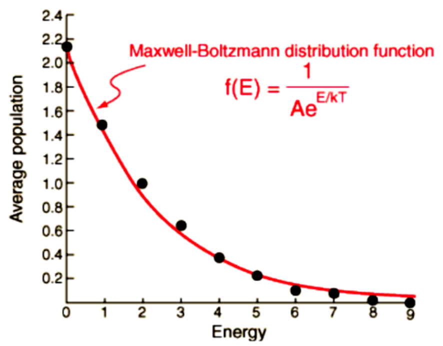

Figure (4-2): The distribution of atoms according to Maxwell-Boltzmann's statistical law.

If ($N_1 < N_2$), the absorption coefficient becomes negative. In this case, the incident wave is amplified instead of weakened due to absorption by the medium, resulting in a positive quantity, which is the gain coefficient G:

$G = -\alpha = \sigma(N_2 - N_1)$ ……….. (4-12)

4-5) Einistien Transactions

Einstein studied the relationship between the probability of transition for the three processes (absorption, spontaneous emission, and stimulated emission). He explained that the rates of absorption, spontaneous emission, and stimulated emission are given by the relationships ($\frac{dN_1}{dt} = -B_{12}N_1\rho$), ($\frac{dN_2}{dt} = -A_{21}N_2$), and (($\frac{dN_2}{dt})_{stim} = -B_{21}N_2\rho$), respectively. When a material is placed inside a cavity for electromagnetic radiation reaches thermal equilibrium, the radiation propagating through the cavity has a spectral distribution whose intensity is given by equation (4-4), which represents the spectral distribution equation for blackbody radiation as found by Planck. Assuming that the atom of the material has two energy levels, and that N_1 and N_2 are the equilibrium states of these levels, and that they are in equilibrium, then there is a probability of each of the three processes occurring between these two levels.

Since the substance is in thermal equilibrium, the number of downward transitions (emission) must equal the number of upward transitions (absorption), i.e.:

$B_{12}N_1\rho = A_{21}N_2 + B_{21}N_2\rho$ ……….. (4-13)

$\rho = \frac{A_{21}N_2}{B_{12}N_1 - B_{21}N_2}$ ……….. (4-14)

$\rho = \frac{\frac{A_{21}}{B_{21}}}{\frac{B_{12}N_1}{B_{21}N_2} - 1}$ ……….. (4-15)

Using Boltzmann's statistics for the state of thermal equilibrium and the distribution of the atoms of the substance across its energy levels (Equation 4-7) and substituting them into Equation (4-15), we obtain:

$\rho = \frac{\frac{A_{21}}{B_{21}}}{[\frac{B_{12}}{B_{21}} e^{-\frac{h\upsilon}{KT}}] - 1}$ ……….. (4-16)

Since the atomic system is in thermal equilibrium, this gives off radiation identical to that of a blackbody (Equation 4-4). Comparing this equation with Equation (4-16) yields:

$B_{12} = B_{21} = B$ ……….. (4-17)

$\frac{A_{21}}{B_{21}} = \frac{8\pi KT}{c^3}$ ……….. (4-18)

The last two equations are referred to as Einstein's equations. Equation (4-17) indicates that the probability of absorption is equivalent to the probability of stimulated emission. Equation (4-18) allows us to calculate the ratio between the spontaneous emission rate and the stimulated emission rate for two energy levels. By substituting Equation (4-18) into (4-4):

$\rho = \frac{A_{21}}{B_{21}} [\frac{1}{e^{-\frac{h\upsilon}{KT}} - 1}]$ ……….. (4-19)

Since ($R = e^{-\frac{h\upsilon}{KT}} - 1$) where R represents the ratio between spontaneous emission and stimulated emission, it follows that:

$\rho = \frac{A_{21}}{B_{21}} \frac{1}{R}$ ……….. (4-20)

$R = \frac{A_{21}}{\rho B_{21}}$ ……….. (4-21)

The spontaneous emission rate under thermal equilibrium conditions is higher than the stimulated emission rate. Therefore, to obtain a laser, thermal equilibrium must be exceeded by having the distribution or qualification density at the highest energy level exceed that at the lowest energy level, i.e., achieving reverse qualification (increasing the radiation density and qualifying the E_2 level).

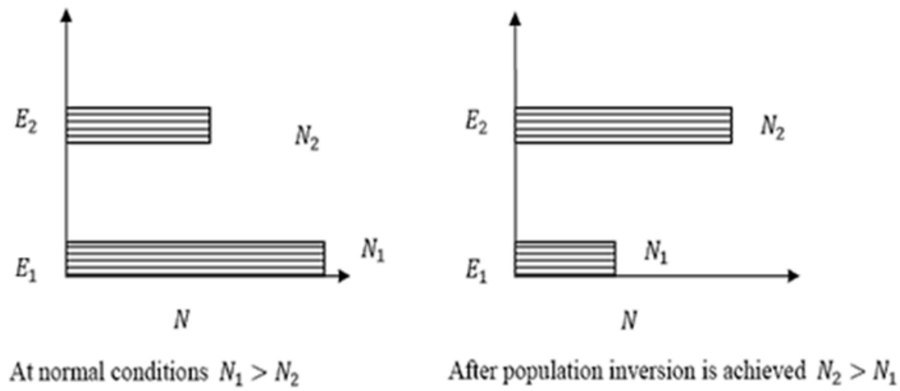

Figure (4-3): Qualification of levels.

4-6) <u>Molecule Energy Levels</u>

A molecule is a structure formed by the bonding of two or more atoms, whether identical or different. Molecular physics is more complex and multifaceted than atomic physics. The total energy of a molecule consists of the energy of the electrons (E_e), which are the outermost unsaturated orbitals in the atomic state. In addition to this energy, the molecule possesses vibrational energy (E_v) and rotational energy (E_r). Comparing the energy differences between the electronic, vibrational, and rotational energy levels in a binary molecule, we find that the distance between rotational energy levels is (1%) of the distance between vibrational energy levels. This vibrational distance is also (1%) of the distance between the electronic energy levels ($E_e > E_v > E_r$). We can conclude that:

1- Transitions between electronic energy levels occur in the range from near-infrared to the visible and ultraviolet wavelengths.
2- Transitions between vibrational energy levels occur in the infrared wavelength range.
3- Transitions between rotational energy levels occur in the microwave wavelength range.

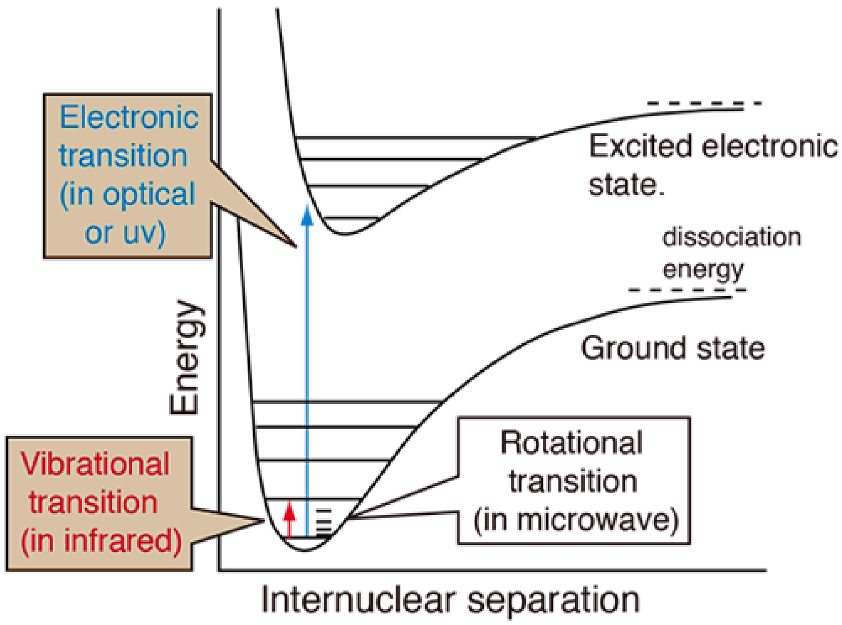

Figure (4-4): Energy levels of a diatomic molecule.

The qualification of energy levels of a molecule in thermal equilibrium is governed by Boltzmann statistics, i.e., the qualification of a rotational vibrational level for a given electronic state is expressed by the equation:

$N \propto g e^{-\frac{\Delta E}{KT}}$ ……….. (4-22)

In this case, the cleavage g is equal to ge, gv, gr, and the total energy of the molecule is:

$E = E_e + E_v + E_r$ ……….. (4-23)

4-7) Spectral Line Broadening Mechanism

The spectral distribution incident on an atom is given by a function called the spectral line distribution function (Δωg). When an atom transitions from one energy level to another, it is described by the spectral line shape of the emission or absorption. The spectral line width is usually determined by the width of the shape at the point where the transition intensity drops by half; this range, $\nu_0 \Delta g$, is called the total line width at mid-intensity (FWHM).

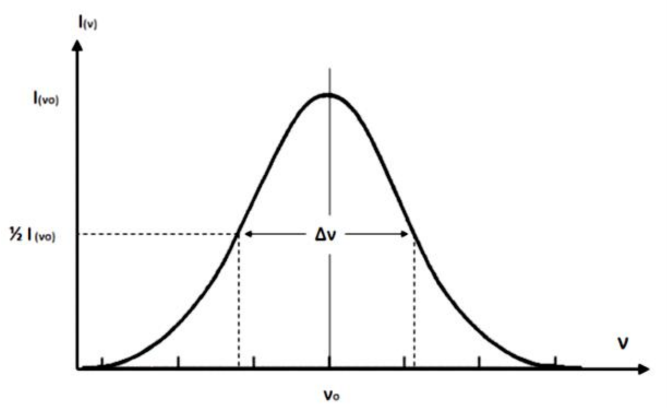

Figure (4-5): Emission spectral line shape.

Spectral line exposure is divided into two types:

1- **Homogeneous exposure:** Here, the transition line of each atom is exposed in the same way and symmetrically, meaning they all have the same frequency around which they are centered, which is the frequency of the same spectral line.

2- **Nonhomogeneous exposure:** Here, the transition frequency is distributed over a narrow range of frequencies. Thus, the atoms of the device as a whole produce a spectral line of a certain width without any exposure to the transition line of each individual atom.

The reasons for spectral line exposure include:

1) Natural Broadening:

The width of the laser beam results from the thickness of the energy levels involved in the stimulated emission process. The energy levels of a number of atoms cannot be represented by a sharp line but rather have a specific thickness.

$Sharp\ line\ width\ \rightarrow \Delta E = 0$ ……….. (4-24)

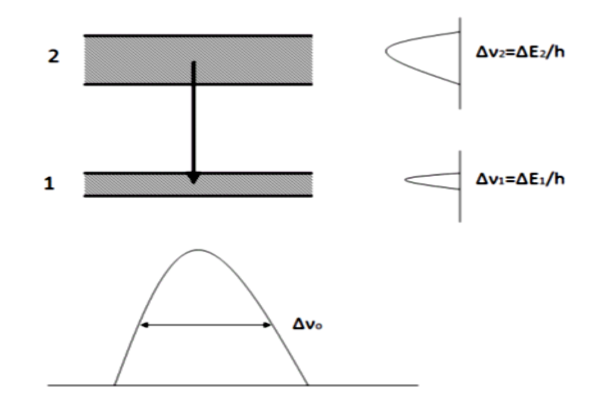

Figure (4-6): Natural broadening of the spectral line.

The longer the lifetime of a level, the narrower its bandwidth, as shown in the equation:

$\Delta\nu = \frac{1}{2\pi\Delta t}$ ……….. (4-25)

Thus, the natural exposure to the spectral line whose frequency equals ν_0 and which is the result between two energy levels is according to the relationship:

$\Delta\nu_\circ = \Delta\nu_1 + \Delta\nu_2$ ……….. (4-26)

$\Delta\nu_\circ = \frac{1}{2\pi\tau_1} + \frac{1}{2\pi\tau_2}$ ……….. (4-27)

The value of the function at the vertex at position ($\nu = \nu_\circ$) is:

$g_{(\circ)} = \frac{2}{\pi\nu_\circ}$ ……….. (4-28)

❖ **Eg.:** What is the normal exposure value of a red neon line (wavelength 632.8 nm) between two energy levels such that (τ_1 = 19.6 ns) and (τ_2 = 18.7 ns)?.

Sol.:

$\Delta\nu_\circ = \frac{1}{2\pi\tau_1} + \frac{1}{2\pi\tau_2} \quad = \frac{10^9}{2\pi 19.6} + \frac{10^9}{2\pi 18.7} = 16.6\ MHz$

2) Collision Broadening (Pressure Broadening):

This is a uniform broadening of the spectral line caused by the collision of a radioactive or absorbing atom with neighboring atoms or with the walls of the container holding it (as in the case of a gas). These collisions produce a force per unit area (represented by pressure) that acts on the spectral lines, causing a broadening of the spectral line. The magnitude of this broadening depends on the time between two collisions, τ_c, and the shape of the resulting spectral line, and is given by the Lorentz function, where the spectral line width is at the midpoint of the intensity.

$\Delta\nu_\circ = \frac{1}{\pi\tau_c} = \frac{\nu_{coll}}{\pi}$ ……….. (4-29)

τ_c can be calculated from the kinetic theory of gases, where this time is estimated as the ratio between the free path rate and the emission rate:

$\tau_c = \frac{(mKT)^{\frac{1}{2}}}{(8\pi)^{\frac{1}{2}} P d^2}$ ……….. (4-30)

Where P represents the gas pressure, d is the diameter of the molecule or atom, T is the absolute temperature, and m is the mass of the molecule or atom. It is clear that the magnitude of τc is inversely proportional to the pressure; therefore, the line broadening increases with increasing pressure, i.e., with increasing collision frequency.

❖ **Eg.:** Calculate the spectral linewidth at mid-intensity for a helium-neon laser at room temperature if the gas pressure is (0.67 mbar) and the diameter of the neon atom is (2.7×10^{-10} m).

Sol.:

$$\tau_c = \frac{(mKT)^{\frac{1}{2}}}{(8\pi)^{\frac{1}{2}}Pd^2} = 0.5\times10^{-6}\ sec$$

$$\Delta\nu_\circ = \frac{1}{\pi\tau_c} = 0.64\ MHz$$

3) Doppler Broadening:

This is an example of non-uniform spectral line exposure where the emitted frequencies are distributed over a narrow range centered around the value ν◦. Doppler line exposure is caused by the random motion of the atom, which moves either in the same direction as or opposite to the direction of the electromagnetic radiation. Thus, the frequency is greater or less than ν◦. According to the Doppler effect:

$$\nu_\circ = \nu(1 \pm \frac{v}{c}) \quad \text{...........} \ (4\text{-}31)$$

v represents the atom's emission and c the speed of light. The spectral line exposure is given by the equation:

$$\Delta\nu_\circ = 7.16\times10^{-7}\nu_\circ\sqrt{\frac{T}{m}} \quad \text{...........} \ (4\text{-}32)$$

4-8) Laser-Matter Interaction

The interaction of lasers with matter varies depending on the wavelength of the laser beam from one laser to another, and the effect of laser energy on matter results from a number of different processes:

1) **Thermal Effect:** Laser energy may be absorbed by colored cells, and the resulting absorption is heat energy. This is the thermal effect of most lasers.
2) **Photochemical Effect:** The laser interacts with molecules inside the cell, and chemical changes occur after this interaction. An example of this type of laser effect is the injection of certain photosensitizing drugs into some tissues.
3) **Mechanical Effect:** The use of pulses from some high-power lasers can lead to the disruption of cellular structures due to the generation of light and sound waves. This mechanical effect is an example of non-thermal laser effects.

Light incident on a material interacts with cells through four mechanisms: reflection, refraction, scattering, and absorption. For the light to have an effect on a tissue, the tissue must absorb it. In the case of transmission or reflection, there is no effect. Scattering of the light means that it is absorbed by a larger area of the material, but the effect is weaker.

The effect of laser radiation on different materials depends on two main factors:

- The material's interaction with the tissue.
- Beam power in terms of energy.

When tissues are exposed to low power for a prolonged period, a photochemical reaction occurs through light absorption, leading to a thermal effect on the tissues. The reaction time decreases with exposure to high power, resulting in photoburning.

Lasers are used for their thermal effect on tissues. The color of the laser beam determines the energy of this thermal action. Therefore, they are used to cut tissues by vaporization. The vaporization mechanism is explained by the rapid transfer of radiation to the cells. The color of the laser beam determines the effectiveness of this effect in different tissues.